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Article (Published Version)

Sovacool, Benjamin K and Martiskainen, Mari (2020) Hot transformations: governing rapid and deep household heating transitions in China, Denmark, Finland and the United Kingdom. *Energy Policy*, 139. a111330. ISSN 0301-4215

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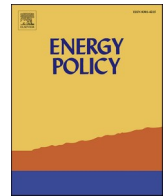
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Hot transformations: Governing rapid and deep household heating transitions in China, Denmark, Finland and the United Kingdom

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ARTICLE INFO

Keywords:

Residential heating
Heat as a service
Energy transitions
Polycentrism
Heat decarbonisation
Energy and climate governance

ABSTRACT

The rapid decarbonisation of heat remains a challenging energy and climate policy priority. In this study, after screening 461 global case studies, we examine four national household transitions in heat, and examine their implications for governance. These transitions were both rapid, involving transformations in heat provision in a short timeframe of 18–35 years; and deep, involving diffusion that collectively reached more than 100 million households and more than 310 million people. From 1995 to 2015, China stimulated industrial research with strong municipal and national targets and policies to the point where they saw adoption rates for solar thermal systems surpass 95% market penetration in many urban areas. From 1976 to 2011, Denmark blended small-scale decentralized community control with national standards and policies to promote district heating so it reached 80% of household needs. From 2000 to 2018, Finland harnessed user and peer-to-peer learning, and innovation, alongside national and European policies and incentives so that heat pumps reached almost a third of all homes. From 1960 to 1977, The United Kingdom coordinated a nationalized Gas Council and Area Boards with industry groups, appliance manufacturers, installers and marketing campaigns so that gas central heating reached almost half of all homes. These four rapid case studies share commonalities in polycentric governance, rooted in (1) equity, (2) inclusivity, (3) information and innovation, (4) ownership and accountability, (5) organizational multiplicity, and (6) experimentation and flexibility. The study affirms that designing the right sort of political and governance architecture can be just as salient as technical innovation and development in stimulating transitions.

1. Introduction

Worldwide, heat remains the largest end-use service for energy, with heating for homes, industry, and commercial applications accounting for about 50% of total final energy consumption (International Energy Agency, 2018). Despite the imperative of decarbonizing heat, however, only about 10% of annual heat production comes from renewable or low-carbon sources (International Energy Agency, 2018). In the European Union, 84% of heating and cooling needs are still met by fossil fuels, and heating and hot water account for 79% of total final energy use in European households, or 192.5 million tons of oil equivalent (European Commission, 2019a). Heat also remains one of the most significant components of European carbon footprints, far more than those from electricity or other household energy services (Dubois et al., 2019).

However, heating also remains one of most difficult sectors or

services to decarbonize. In the residential sector, the structure of household heat consumption is often embodied in both existing long-lived infrastructures and social practices, both of which make it resistant to change (Hansen 2016, 2018). Royston (2014) attributes part of the problem to the multiple goals households want to achieve with heat, many of which conflict, including goals of thermal comfort, saving money, mitigating climate change, or maintaining the right temperature for another person, pet, or material object. Vivid Economics and Imperial College (2017: 2) write that:

Decarbonizing buildings is highly challenging, first, because many of the technologies to deliver low carbon heating – heat pumps, biomass boilers, hydrogen networks – have higher capital cost than incumbent technologies without delivering a higher level of service from the perspective of the customer. Second, changing heating technologies can be disruptive.

Other studies emphasize the socio-technical challenge of household

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Table 1
Summary of four rapid household heating transitions.

Country	Years	Technology	Diffusion across national population	Polycentric component	Description
<i>China</i>	1995–2015	Solar thermal hot water and space heating	19.2% (approximately 263.5 million people) ^a	Stimulated industrial research with strong municipal and national targets and policies	Household use of solar heating grows from a few thousand units in the 1990s to 1 million units being manufactured each year by 2015, corresponding to 70 million square meters of collectively installed solar collection; some urban areas saw adoption rates surpass 95% of homes; China held 76% of worldwide capacity by 2015 and the total number of installed units nationally surpassed 85 million; solar thermal systems displace an estimated 75.7 million tons of carbon dioxide per year in 2015
<i>Denmark</i>	1976–2011	District heating networks and combined heat and power	28.9% (approximately 1.61 million people) ^b	Blended small-scale decentralized community control with national standards and policies	Reversed Danish dependence on oil for heating in five years; converted 800,000 heating systems and installed 45,000 km of heat pipes; provided 80% of household heating needs in 2011; reduced national carbon dioxide emissions by 20%
<i>Finland</i>	2000–2018	Heat pumps	33.9% (approximately 1.87 million people) ^c	Harnessed user and peer-to-peer learning and innovation alongside national and European policies and incentives	Diffusion grew 613-fold from approximately 1500 heat pumps in 2000 to 930,000 in 2018. The majority of heat pumps have been installed in detached and semi-detached houses; 70% of new homes choose a heat pump
<i>United Kingdom</i>	1960–1977	Natural gas central heating	77.2% (approximately 43.4 million people) ^d	Coordinated a nationalized Gas Council and Area Boards with industry groups, appliance manufacturers, installers and marketing campaigns	Converted 40 million appliances and 14 million homes (almost half of <i>all</i> homes at that time) to run on natural gas from the North Sea, rather than town gas; a majority of these conversions happen in just 10 years' time; Corresponding fuel consumption went from almost entirely town gas in 1966 (110,000 GWh), to almost entirely natural gas (443,000 GWh) by 1977; 92% of the population of the UK has a gas grid connection

^a In 2015, 85 million solar thermal heating systems were reportedly installed in China. With the United Nations reporting an average household size of 3.1, this would equate to roughly 263.5 million people reached out of 1.371 billion.

^b According to the OECD, Denmark had 961,000 households in 2011, and an average reported household size of 2.1 (below the OECD average of 2.6). An 80% diffusion rate therefore affected 1.614 million people, or 28.9% of the population of 5.58 million.

^c Statistics Finland reports that the average household size for the country was 2.02 persons in 2016. The 930,000 heat pumps sold would therefore serve roughly 1.87 million people, or 33.9% of the country's 5.52 million people.

^d The Office for National Statistics reports that in 1977, the average household size for the United Kingdom was 3.1. With 14 million homes reached, the gas central heating transition would have affected 43.4 million people, or 77.2% of the national population of 56.19 million.

Source: Authors, based on data presented in the case studies below. GWh = Gigawatt-hours.

heat decarbonisation as being a complex problem, involving a mix of infrastructure and building stock, patterns of incumbency and path dependence, and socioeconomic drivers such as income and poverty (Eyre and Baruah, 2015; Wade et al., 2016; Gross and Hanna, 2019).

Despite this imperative of decarbonizing heat, the International Energy Agency (2012: 14) cautioned that “heating and cooling remain neglected areas of energy policy and technology.” Five years later, the International Energy Agency (2017) warned that buildings in general, and heating and cooling practices in particular, were off track in terms of their sustainability to a greater extent than many other areas of the energy sector or economy. Connolly et al. (2014) also add that within Europe specifically, heat remains a critically important but often neglected area of energy policy focus. Vivid Economics and Imperial College (2017: 2) add that in the domain of heat, “there is a need to learn lessons from case studies of best practice around the globe.”

With this goal in mind, after screening 461 global case studies, this study examines four rapid and deep transitions in household heat (and hot water) provision: solar thermal systems in China from 1995 to 2015, district heating in Denmark from 1976 to 2011, heat pumps in Finland from 2000 to 2018, and gas central heating in the United Kingdom from 1960 to 1977. We categorize these transitions as rapid, as they all occurred in a timespan of 35 years or less; and deep, because they changed the provision of heat for a collective population of more than 310 million people. The study also shows that these four rapid and deep case studies share commonalities in governance, rooted in (1) equity and the dissemination of co-benefits, (2) inclusivity and local involvement, (3) information and innovation, (4) ownership and accountability, (5) organizational multiplicity, and (6) experimentation and flexibility.

The study affirms, apart from informing policy for low-carbon residential or household heat, that polycentric energy and climate governance are important alongside the design or innovation of heating technologies and systems. It therefore supports the burgeoning literature on the value of polycentrism in energy and climate decision-making. Ostrom called “polycentric systems” those that are characterized by multiple governing authorities at differing scales rather than a mono-centric unit (Jordan et al., 2015; Sovacool, 2011; Sovacool et al., 2018; Ostrom, 2010a, 2010b). Polycentrism reflects the recognition that global climate governance has increasingly come to encompass action by sub- and non-state actors (Jordan et al., 2018; Cole, 2015; Hale, 2016; Poocharoen et al., 2012). What makes a polycentric approach so attractive is that it avoids using the “government” or the “state” as the single point of reference in steering a transition or a program. As other authors who adhere to a polycentric approach have noted, “polycentric networks transcend the traditional ideas of jurisdictional integrity in state-centric systems” (Skelcher, 2005: p. 89).

2. Research methods, analytical strategy and conceptual approach

The core method used in this study is a qualitative, comparative, case study approach selected after a global screening process, and drawn from a synthesis of peer-reviewed literature as well as current reports and documents related to the four heating transitions. The cases have been selected on the basis of their scope (all involve a heating technology or service), speed (all involved rapid diffusion), and contemporaneity (all include modern technologies and have occurred within the past fifty years).

To select cases, the authors utilized an analytical screening process that began with a possible sample of 461 global case studies related to the adoption of heating technology and systems, and ended with four case studies. We first searched Scopus for any case study, at any scale, concerning the adoption of a new heating technology, system, or device, published in English in the past fifty years (i.e. from 1970 to 2019). This resulted in 461 possible cases. We then began to narrow the cases according to the following protocol:

- It had to be a case study at the *national* scale, this excluded small pilot or demonstration projects (399 left) as well as case studies of smaller units such as individual buildings or campuses (250 left) or cities (199 left);
- It had to be a case looking at *residential household* heating, congruent with the project funding the research but also given the imperative of decarbonizing household heat (Dubois et al., 2019) (65 left);
- It had to be *modern*, a case study completed in the past half century, with no projects ending before 1970 (59 left);
- It had to have sufficient *availability of data*, i.e. at least 5 published sources of credible information (14 left);
- It lastly had to be an “extreme” or “clear cut” case of success, i.e. a case study that saw successful diffusion of heating technology or a *rapid heating transition* with a time period shorter than 50 years.

This last point about rapidity draws from Grubler’s (2012) assessment of historical energy transitions in Europe across 16 countries and two waves of transition (phase-in of coal, phase-in of oil/-gas/electricity). Grubler noted across these cases that the slowest transition had a diffusion speed of 160 years (England), the fastest 47 years (Portugal). Sovacool’s (2016) review of the speed of energy transitions also affirms this point about many conventional energy transitions taking centuries; we interpret this to mean that fast transitions are those that can take decades to half centuries.

As Table 1 indicates, our four selected case studies involve four different heating technologies (solar thermal, district heating, heat pumps, gas central heating) in four very different countries (China, Denmark, Finland, and the United Kingdom) over different time periods, although all have taken place within the past half-century. All also meet our definition of a “rapid” transition, with transitions occurring over a timespan of 18–35 years. In China, the top two end uses or services provided by solar thermal are hot water and space heating, making them similar to heat pumps (Huang et al., 2019). China has been for at least two decades, and remains, the undisputed world leader in the manufacturing, use, and export of household solar thermal technologies (Liu et al., 2010; Hu et al., 2012; Goess et al., 2015; Huang et al., 2017). Urban et al. (2016) even refer to solar thermal systems as the “undiscussed protagonist” in the Chinese low carbon transition. Denmark leads all of Europe in the per capita use of district heating and were also able to convert almost a million household heating systems in less than five years (Sovacool, 2013). Finland is one of the world leaders in the penetration rates for heat pumps (International Energy Agency, 2019). In June 2019, the Finnish Heat Pump Association SULPU estimated that 930,000 heat pumps had been sold in the country of only 5.5 million people (SULPU, 2019a; personal communication). Heat pumps have become a common choice for heating in Finland, in many instances replacing oil-fired heating systems. The United Kingdom exhibits a striking transition involving a concert of state and private sector actors implementing a 10-year plan to convert gas supply and all domestic appliances from manufactured or town gas to natural gas, mostly from the North Sea (Foxon et al., 2013). The UK transition involved “an extraordinarily challenging 10-year conversion of the 40 million appliances of 14 million consumers by 1977” (Pearson and Arapostathis, 2019). These four programs also feature different temporalities: the UK program was a legacy of the 1960s and early 1970s; the Danish program a product of the later 1970s, 1980s, and 1990s; the Chinese program made the bulk of its diffusion 1990s and 2000s; Finland represents the most recent transition, occurring in the 2000s and 2010s.

The four cases also share in common an element of polycentrism, as Table 1 also summarizes. Polycentric approaches – those that incorporate multiple scales and multiple stakeholder groups at once – are often able to harness the benefits of global and local action together instead of having them tradeoff (Ostrom 2010a, 2010b). One key component behind the polycentric model is its emphasis on interaction between local, state, national, and global scales. Polycentric approaches imply that the sharing of power between these scales must be seamlessly

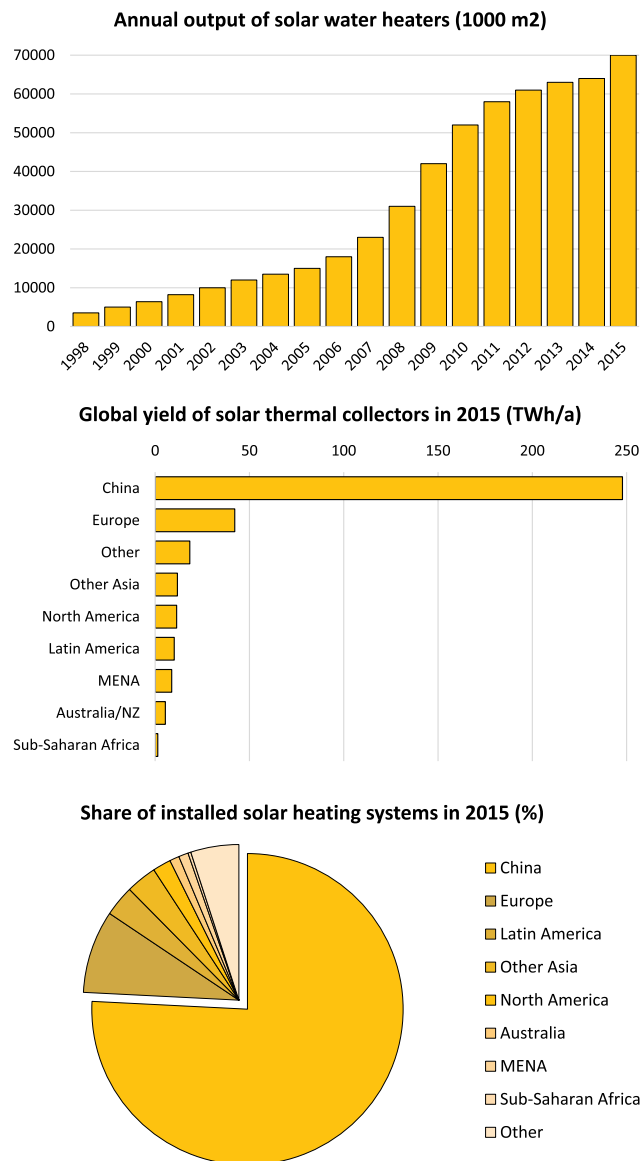


Fig. 1. The rapid Chinese transition to solar heating, 1998 to 2015
Source: Authors' compilation, based on [Tao \(2010\)](#) and [Huang et al., \(2019\)](#).
Note: MENA = Middle East and Northern Africa. NZ=New Zealand. TWh = Terawatt-hours.

mangled ([Schapiro, 2005](#)).

The governance literature suggests that polycentrism can harness the power of diverse perspectives, build coalitions, and promote cooperation rather than competition ([Ostrom 2010a, 2010b](#); [Jordan et al. 2015, 2018](#); [Sovacool et al., 2018](#)). Having multiple organizations and institutions involved in a transition, or policy enabling such transition, means that different actors with distinct perspectives review a problem. Moreover, involving stakeholders beyond the realm of government (such as business leaders or members of environmental groups) can build coalitions and promote cooperation rather than competition ([Hess 2018](#); [Hess 2019](#)). This diversity of perspective produces a broader variety of potential solutions and provides better experimentation. Overlapping jurisdiction and inclusion can be pivotal in encouraging more appropriate levels of government to respond to issues such as climate change and energy. Polycentrism also provides more opportunities to involve and benefit from a more diverse set of players in the policy-making process. Put another way, polycentrism captures the benefits of local action without compromising many of the benefits of global action

(such as consistency and equity). [Brown and Sovacool \(2011\)](#) argue that polycentric approaches can also promote dialogue, provide a regulatory safety net, enhance accountability, and maintain economies of scale in the context of energy security and climate change mitigation. Our four cases certainly seem to affirm many of these points.

3. China: Solar thermal heating (1995–2015)

China offers an example of a rapid transition to solar thermal space and water heating in households from the mid-1990s to 2015.¹ The primary logic behind this transition was a desire to promote “solar cities” and spotlight ongoing efforts to reduce air pollution as well as mitigate climate change. However, the transition was also coupled with political goals relating to national planning and innovation, as well as emerging cultural norms about hot water use and notions of hygiene and self-sufficiency. Strong solar resources across most of the Chinese territory also facilitated adoption patterns.

Within the Chinese solar thermal heating transition, a typical household solar thermal system costs between €300 to €500 (or \$350 to \$600) ([Tao, 2010](#)). Especially prominent has been the diffusion of evacuated or vacuum tube solar water heaters (rather than flat plate collectors), across both rural and urban areas. As [Fig. 1](#) reveals, China grew from 3.5 million square meters of solar thermal production in 1998, to 70 million square meters in 2015, a 20-fold increase. This corresponds from only a few thousand units being adopted in the early 1990s to more than one million being made each year by 2015 ([Huang et al., 2017](#); [Urban et al., 2016](#)). As [Huang et al. \(2017: 156\)](#) write, “The expansion of solar hot water systems in urban China has been spectacular.” That year, in 2015, China held almost 76% of global installed capacity for solar heating devices and represented 69.4% of global solar heating production in Terawatt-hours. In some urban areas and in Chinese “solar cities”, such as Rizhao, adoption rates are greater than 95% of all households ([Huang et al., 2017](#)). During some particular periods, such as the late 1990s, the market grew by more than 30% annually ([Huang et al., 2019](#)), and China also manufactures most of its solar systems domestically, becoming a major industrial producer and consequent global exporter—the top four manufacturers of solar thermal systems are all Chinese ([Huang et al., 2019](#)). [Urban et al. \(2016\)](#) reported that approximately 3000 solar thermal firms are based in China, with 1800 making solar water heaters and 1200 supplying components; they also estimated that the annual market volume for solar thermal in China surpasses \$2 billion.²

The beginnings of the solar thermal transition in China are often traced back to the science and research foundations erected in the 1970s and 1980s. It was at this time that the solar industry made a “break-through” in coating technology for solar vacuum tubes (also called “evacuated tube collectors”), after the introduction of Canadian designs for the production of copper-aluminum composite absorbers and self-designed anodic oxidation selective coating ([Hu et al., 2012](#)). However, progress was slow due to high initial costs and low energy production potential from the systems during the winter months. In the late 1980s, demand for hot water began to become a more widespread cultural convention, with residents bathing more frequently and also preferring

¹ The term “solar thermal” refers to a bundle of related but still distinct technologies and market applications: urban domestic hot water, rural domestic hot water, urban and rural space heating, and in some cases industrial and agricultural processing. Roughly 95% of solar thermal adoption has been hot water systems ([Huang et al., 2019](#)).

² [Urban et al. \(2016\)](#) reported that the top solar thermal firms by volume of manufacturing were: Himin Solar Energy, Shandong Long Guang Tian Xu Solar Energy, Shandong Linuo New Material, Jiangsu Sunrain New Energy Group, Shandong Sangle Solar Energy, Shandong Linuo Paradigma Solar Energy, Jiangsu Huayang Solar Energy, Beijing Tianpu Solar Energy Industry, Beijing Huaye Solar, New Energy, and Guangdong Fivestar Solar Energy.

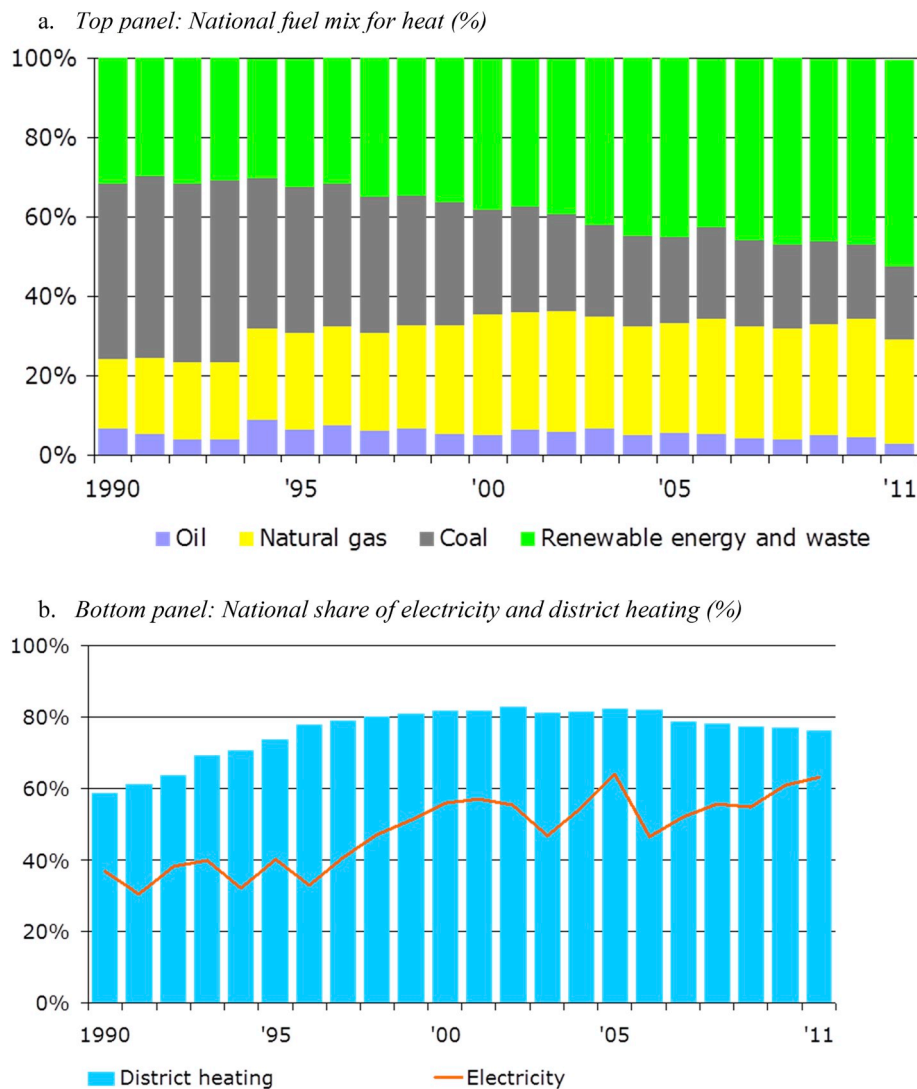


Fig. 2. The rapid Danish transition to district heating, 1990–2011.
Source: Authors, with data from the Danish Energy Authority.

warmer homes, especially in urban areas (Huang et al., 2017; Yu and Gibbs, 2018). Furthermore, solar systems were better attuned to peaking needs for hot water, heating and cooling in the Southern provinces, which had greater summer peaks, but also problems with electricity distribution and shortages (Li et al., 2011; Urban et al., 2016).

A pivotal moment for the solar thermal industry was 1995, when the Himin Group was established and became the largest manufacturer in the world within a few years (Yu and Gibbs, 2018; Goess et al., 2015). The Himin Group made substantial efforts to popularize knowledge about solar energy nationally among both households and local planners, in tandem with further technological improvements from the Beijing Solar Energy Research Institute in the production of glass vacuum tubes and heat exchangers. Multiple studies refer to this decade as the most important in terms of production and industrialization of the solar heating sector, with manufacturing and distribution efforts scaling up significantly (Hu et al., 2012; Urban et al., 2016). These high growth rates in turn attracted new entrants into the sector, with more than 500 small and medium size firms entering the market alongside the large incumbents (Goess et al., 2015).

The acceleration of solar thermal diffusion continued and even increased into the 2000s, with solar in particular featuring prominently in the *Solar City Strategy* of many urban areas (Yu and Gibbs, 2018) and the 2006 Law of Renewable Energy implemented by the National

People's Congress, which signified government commitment to the development of solar water applications as well as industrial manufacturing (Tao, 2010). The 2006 Law for example set national aims that 15% of total energy consumption would be supplied by renewables by 2020, and that installed solar collectors specifically should reflect 300 million square meters by 2020. National subsidies were also implemented that gave rural households a 13% subsidy to cover the partial cost of a solar water heater. From 2006 to 2008, the national government also supported more than 350 renewable energy demonstration projects with financial support from the national government, 41% of these were solar heating projects. In 2009, the Ministry of Finance and Construction decided to further support renewable energy in buildings in demonstration cities, offering \$7 million to \$12 million (¥50 million to ¥80 million) of subsidies. In tandem with this, more than 80 cities and 20 provinces and autonomous regions issued compulsory policies for installing solar hot water systems on new buildings, with some provinces such as Beijing and Shandong even going beyond this to subsidize almost the entire installation costs (Tao, 2010).

The 2000s not only saw consistent support for solar thermal at the national level, but at the city and provincial and sub-national level as well. Hainan, Jiangsu, Hebei, Henan, Shandong and Ningxia and cities such as Shenzhen, Jinan, Rizhao, Yantai, Zibo, Qingdao, Xingtai, Qinhuangdao, Zhengzhou, Sanmenxia, Huhhot, Nanjing and Wuhan all

introduced policies in 2007 that required installing solar water heaters as part of every new building (Urban et al., 2016). During this period, from the end of the 1990s to 2010, China's annual output of solar water heaters increased 15 times from 3.5 million square meters to 52 million square meters. As another sign of success, by 2010 more than 2800 manufacturers of solar thermal systems existed nationwide, mostly concentrated in the Zhejiang, Jiangsu, Shandong, and Yunnan regions (Tao, 2010). Hu et al. (2012) confirm that this decade saw "rapid growth" in solar thermal adoption. Tao (2010) report that from 1998 to 2010, 168 million square meters of solar water heating were installed nationwide, with an average annual growth rate from 1998 to 2010 of 80%.

Both sustained growth and stronger government support continued into the 2010s, which saw the 12th Five Year Plan (2011–2015) and the 13th Five Year Plan (2016–2020) framing solar energy as a crucial part of the country's climate change action framework (Huang et al., 2018). Explicit and additional policy support for solar thermal included:

- A 2017–2021 Clean Heating Plan in Winter in Northern China that set higher targets for solar and clean heating systems;
- A 2015–2020 Guideline on Space Heating with Renewable Energy which promoted building-integrated solar heating systems;
- A 2015–2020 National Building Energy Efficiency and Green Building Development program that promoted 2 billion square meters of solar heating systems for public buildings;
- A 2015–2020 National Solar Energy Development program aiming to see solar hot water and space heating reach 300 million rural families (and reach 20 million square meters of industrial heating applications);
- A 2015–2020 National Renewable Energy Development policy that sought to see solar thermal energy surpass 800 million square meters by the end of 2020 (Huang et al., 2019).

As a result, even more provincial and city governments in particular introduced incentive schemes for solar thermal as well as the emergence of building-integrated solar water heaters in urban areas and applications for larger-scale commercial and industrial processes (Goess et al., 2015; Li et al., 2011). Huang et al. (2019) note that even while the market for solar thermal slowed by 40% from 2012 to 2017, they still expect very high market shares by 2022. Urban et al. (2016) report that while 30 million households used solar water heaters in 2009, the number surpassed 85 million solar thermal heating systems in 2015.

In sum, the Chinese success story with solar thermal heating underscores the value of having on the supply side a concerted mix of proactive government support at all levels (city, province, national) with strong networks of dealers and a large industrial manufacturing base, and on the demand side a uniform desire for warm homes and hot water across urban and rural areas.

4. Denmark: District heating (1976–2011)

The Danish transition to district heating has fundamentally different dynamics and motivations than the Chinese case. Its primary goal was to minimize dependence on fossil fuels and improve the efficiency of their fleet of thermoelectric power plants. Secondary goals included promoting decentralized energy supply and establishing heat networks, minimizing air pollution and carbon emissions, and maintaining a degree of self-sufficiency in energy production.

Danish policymakers aggressively encouraged the use of district heating, and combined heat and power (CHP), units for both electricity generation and household heating in the 1970s.³ For instance, since the

oil shocks of the early 1970s to 2011, CHP use in aggregate has expanded by a factor of four from 49,196 TJ to 200,870 TJ, and it has become mostly fueled by natural gas alongside low-carbon renewable sources such as biomass, straw, and solar. As Fig. 2 reveals, cogeneration provides more than 50% of all electricity and 80% of district heat consumed in Denmark through approximately 45,000 km of pipes, making it one of the leaders in Europe (Münster et al., 2012; Lund et al., 2010), with countries such as Latvia, Estonia, Sweden, Finland and Iceland following Denmark's example and having high percentage of citizens accessing district heating (Finland and Sweden close to 50%, Latvia and Estonia over 60% and Iceland over 90%) (Colmenar-Santos et al., 2016).

From 1955 to 1974, almost all heating in Denmark was provided by imported fuel oil, which meant the oil crisis had particularly painful impacts on the country's economy (Maegaard, 2010). In 1973, when oil prices rose astronomically, 85% of Denmark's electricity came from oil, its transport sector was almost entirely dependent on it, and oil provided more than 90% of the nation's primary energy supply (Lund et al., 2010; Lund, 2010; Lunda, 2000). The Danish Energy Agency was created in 1975 to help steer and manage a more strategic energy policy for the country.

These efforts culminated in the Danish Energy Policy of 1976, which stipulated the short-term goal of reducing oil dependence, and it stated the importance also of building a "diversified supply system" and meeting two-thirds of total heat consumption with "collective heat supply" by 2002 (Sovacool, 2013). Moreover, it sought to reduce oil dependence to 20%, an ambitious goal that involved the need to convert roughly 800,000 individual oil boilers to switch to natural gas and coal (Mortensen and Overgaard, 1992). In a mere five years—from 1976 to 1981—Danish electricity production changed from 90% oil-based to 95% coal-based (Lund and Hvelplund, 1997). Stipulations in favor of CHP were further strengthened by the 1979 Heat Supply Act, whose purpose was to "promote the best national economic use of energy for heated buildings and supplying them with hot water and to reduce the country's dependence on mineral oil" (Mortensen and Overgaard, 1992).

To achieve the stated purposes of these two major acts, a "radical restructuring" of the heat supply system commenced, converting practically all oil-based systems to something combusting coal, natural gas, or biomass (Mortensen and Overgaard, 1992). In undertaking this campaign, Parliament delegated authority away from Copenhagen to local municipalities, and emphasized the viability of both natural gas and biomass for CHP systems. In 1979, for example, the Danish Parliament established a national natural gas project based on offshore gas fields in the North Sea, and in 1981 district heating systems utilizing straw were introduced leading to "serious straw-for-energy expansion" (Voytenko and Peck, 2012). In 1986, the Danish Energy Agency, Steering Group for Renewable Energy, and the Danish Board of Technology encouraged even more decentralized CHP generation and built straw demonstration plants ranging from 100 to 3000 kW. Overall, Denmark invested about \$15 billion from 1975 to 1988 in CHP systems and transmission networks (Mortensen and Overgaard, 1992).

The 1990s saw continued support for CHP units. In 1990 a "triple tariff" system was introduced which paid CHP operators based on their provision of peak, medium, or low-load electricity and also granted them an energy "premium" of an extra 1.3 €¢ per kWh. At the same time, the Danish Parliament placed a moratorium on coal use and announced that "no new coal-fired power plants would be permitted," a proclamation later formalized in 1997 when the Danish parliament passed the "coal stop," functionally outlawing the construction of new coal fired power stations, with exceptions given only to two 450 MW plants. Coupled with these improved tariffs and the moratorium on coal, the government promoted environmentally friendly zoning to advance electricity investments in towns and villages outside major cities. Based on these trends, the mid-1990s saw a thriving market for CHP, with about 350 district heating companies operating, including four regional

³ Combined heat and power, sometimes referred to as cogeneration, refers to power plants that can simultaneously generate electricity as well as useable heat or steam. Some primarily generate heat with electricity as a by-product, others generate electricity with heat as a by-product.

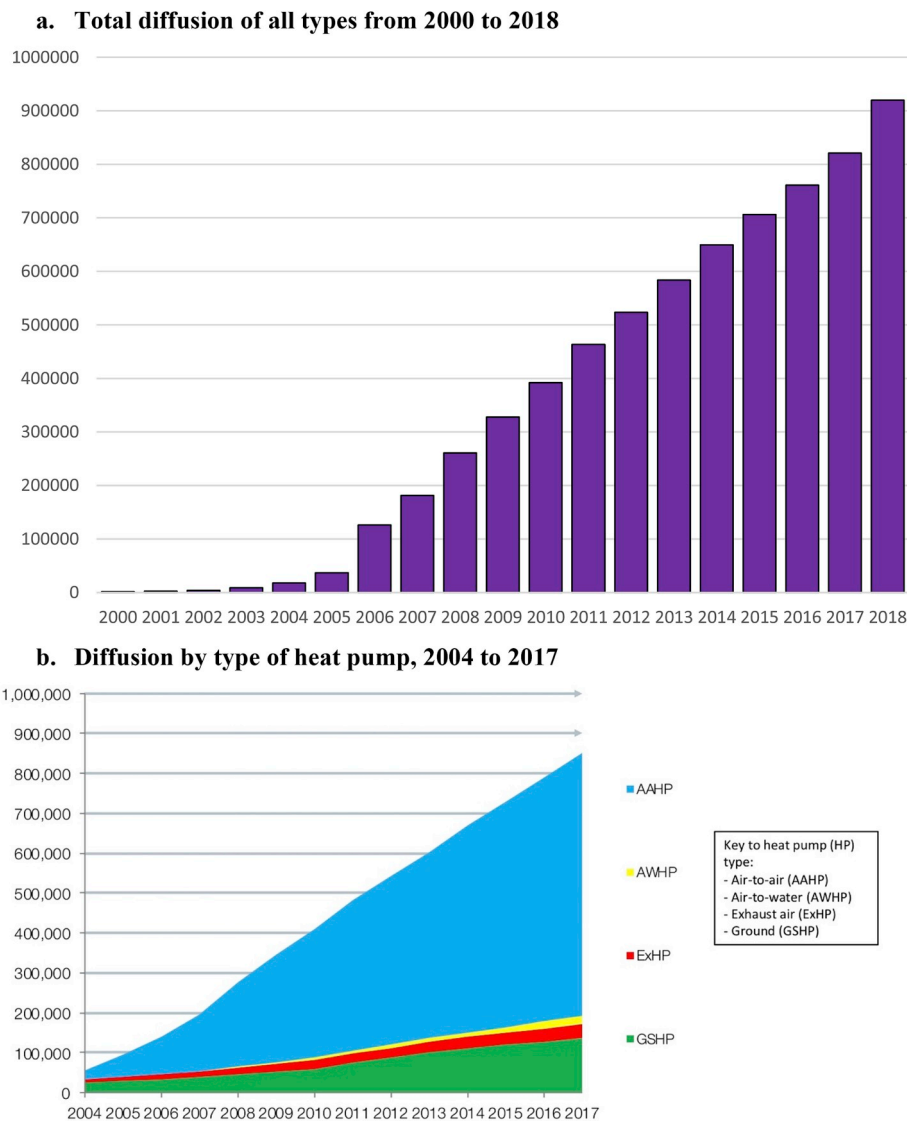


Fig. 3. The rapid Finnish heat pump transition, 2000 to 2018.

Source: Authors, based on data from Hyysalo et al., (2018), SULPU 2018a and SULPU 2019a.

or inter-municipal systems, linked via heat transmission networks (Mortensen and Overgaard, 1992).

This wave of environmentally friendly conversions and efficiency improvements drove significant investment in the CHP market. From 1990 to 1997, more than three-quarters of all new capacity added to the Danish grid consisted of small CHP plants for district heating or industrial use. These had to be fueled by natural gas or straw (Lehtonen and Nye, 2009) to the point where by 2011 more than 50% of CHP fuels come from renewable resources and 25% comes from natural gas.

5. Finland: Heat pumps (2000–2018)

The Finnish heat pump transition was driven by a mix of geographic, demographic, policy and environmental factors. Finland has district heating networks largely located in cities, but other areas having oil heating systems have more polluting and arguably more expensive forms of heat, creating a strong niche market for heat pumps. A large number of new build houses suitable for heat pump technology further opened the market, along with taxation of fossil fuels, a culture of building decent size homes, with high energy efficiency measures such as triple glazed windows and high levels of insulation, that captured on the allure of heat pumps helping make more sustainable homes.

The Finnish household heat transition has involved heat pumps, mostly air source (i.e. those that extract heat from the air), usually for space heating and hot water, and ground source (i.e. those that use geothermal heat) for both space heating and hot water (Soltani et al., 2019).⁴ Many heat pumps have also been installed as hybrid systems, often combined with wood-based fireplaces for instance. Finland provides a good example of a context in which heat pumps have seen a rather rapid uptake in a short space of time. In this country, which is located in the Nordic region with temperatures in the winter months staying below freezing for long periods, heat pumps have become a

⁴ There are several different types of heat pumps, those that extract heat from air and those that extract heat from the ground (geothermal). Geothermal heat from ground source heat pumps (GSHP) can be used for different purposes including providing heating and cooling for buildings, generating electricity and providing hot water (Soltani et al., 2019). There are different types of air source heat pumps, some of which only provide heated air (air-to-air heat pump (AAHP)), while others can also provide hot water (air-to-water heat pumps (AWHP) and exhaust air heat pumps (ExHP) for heating and cooling. Although less common in other countries, the Finnish case also involves air-to-water heat pumps (AWHP) and exhaust air heat pumps.

popular choice for many householders. The Finnish heat pump association SULPU has estimated that in 2018, 930,000 heat pumps had been sold in Finland (SULPU, 2019a; personal communication) – a significant number compared to the 1500 sold in 2000 (see Fig. 3). It is also a substantial number given Finland has a total population of 5.5 million people and just over 2.7 million households, meaning they have diffused to about 34% of all households. In 2018, Finnish residential dwellings consumed 5125 GWh of heat pump generated space heating energy, of which 83.4% was consumed by detached and semi-detached houses, 9.3% by terraced houses, 5.3% by leisure homes and 2.0% by blocks of flats respectively (Tilastokeskus, 2019). There are three Finnish heat pump manufacturers (Gebwell, Oilon and Lämpöässä), while most international models (e.g. Daikin, Hitachi, Mitsubishi, Panasonic, Toshiba) are also available in the Finnish market. Approximately 70% of new built small houses choose a heat pump (SULPU, 2018), and roughly 5000 oil boilers are replaced with a heat pump each year (SULPU, 2018).

The history of heat pumps in Finland is rather young, with a small number of ground-source heat pumps (GSHP) installed in the 1970s following the oil crises and examples of mainly ground source heat pump technology being deployed in Sweden (Lauttamäki, 2018). At the time, the government supported a move away from fossil fuels by for example providing heating system renovation grants (Lauttamäki, 2018) and funding energy innovation, including ground source heat pump factories (Majuri, 2016). By the early 1980s, 15 small GSHP factories existed in Finland (Majuri, 2016). However, the sector struggled due to heat pumps having technical problems and being of poor quality (Heiskanen et al., 2011; Majuri, 2016). Furthermore, many experts at the time considered that heat pump technology was not suitable for the Finnish context, given the country's cold climate (Hyysalo et al., 2018). By 1984, an estimated 10,000 GSHPs had been sold in Finland (Lauttamäki, 2018), but the combination of a drop in oil prices and heat pump technology's negative reputation led to the bankruptcy of most Finnish heat pump suppliers by the mid 1980s (Lauttamäki, 2018; Majuri, 2016).

In early 1990s, a new wave of heat pumps started to emerge in Finland, with also air source heat pumps (ASHPs) entering from Sweden, where the Swedish government had supported the creation of a heat pump market (Heiskanen et al., 2011). GSHPs too started to take off again, following technological developments, especially the use of vertical borehole drilling techniques that proved well-suited to the Finnish geological context (Lauttamäki, 2018). In these early days of the Finnish heat pump transition, the technology was bought into by small companies and individual enthusiasts, and sales never surpassed a few hundred per year. By 1999, however, several heat pump suppliers were operating and competing in the Finnish market, and a national heat pump association, SULPU, was officially established in 1999 by a heat pump entrepreneur and a heat pump researcher, with support from the government energy efficiency agency Motiva (Heiskanen et al., 2011; Majuri, 2016). The entrepreneur had a vision that 1 million heat pumps would be sold in Finland by 2020 (Virkkunen, 2017). By 2000, Finland had grown a small supply chain of about 10–15 heat pump resellers but sales remained low. The sector needed better standards, especially for training, certification and quality control, which were seen as key in a developing market—and aiding the previously tarnished reputation of heat pump technology.

From 2000, government policies and targets increasingly encouraged a switch from fossil fuel based heating systems to renewable options, for example heating oil taxes more than doubled between 2004 and 2017 (Lauttamäki and Hyysalo, 2019) and many oil heating systems have been replaced with heat pumps since (Lauttamäki, 2018). In 2001, a National Climate Strategy outlined plans for the decarbonisation of heat, mentioning for example heat pumps as a mature technology of which use could be increased in new buildings in particular (TEM, 2001). At the same time, energy efficiency requirements of new buildings were tightened by 30% (TEM, 2001). One of the longest-standing support mechanisms for heat pumps, which did not in fact stem from

energy policy, but from general taxation policy, was introduced across the country in 2001 (Lauttamäki, 2018). “A deduction of household expenses” is a tax incentive on labor costs related to work undertaken at one's home (first trialled in a few regions in 1997), and includes also the installation costs of heat pumps (Vero, 2019).

Subsequent national climate and energy strategies were published in 2005, 2008, 2013 and 2017 (TEM, 2005; 2008, 2013; 2017), all continuing on the heat decarbonisation pathway with support for renewables and increasingly tightening building regulations. In 2005, the government concluded that support for heat pumps had focused on information campaigns (Finland had started energy advice for consumers in 1996 (Kern et al., 2017)), and securing high standards and reliability of the technology (TEM, 2005). Furthermore, subsidies for replacing oil heating systems had been introduced in 2003 and specific energy renovation grants were available between 2003 and 2005 that also supported heat pumps (Kern et al., 2017). Certification schemes for both heat pumps and installers were important for creating customer confidence (Heiskanen et al., 2014a, b), and together with training, improved the expertise and credibility of the industry in the early 2000s (Majuri, 2016). Largely due to the work of SULPU, training and standards for installations improved in during the 2000s (Lauttamäki, 2018), boosting the reputation of the sector and leading to increased sales. In addition, Motiva ran several heat pump trials during 2000s, providing a wide-range of publications and guidelines (Motiva, 2019), as well as a list of certified installers (Lauttamäki, 2018).

In addition to the government's clear objective of supporting heat pumps as part of a package of decarbonizing heating, the early 2000s also saw the arrival of user-led online heat pump discussion forums. These provided dedicated platforms for users to share experiences on different heat pumps models, also providing unofficial advice on issues such as heat pump sizing, costs and thoughts on specific manufacturers (Hyysalo et al., 2018). Hyysalo et al. (2018) have attributed these online forums as important parts of the heat pump transition, classifying them as user-intermediaries who can aid diffusion. Their role was important also in showing that heat pumps were indeed suitable in the cold Finnish climate, leading to user-led innovation (Hyysalo et al., 2013b).

In 2008, a clear national target for heat pumps was set: 5 TWh by 2020, which formed a part of a larger target of 38% of energy end use to come from renewables by 2020 (TEM, 2008). In 2009, Finland was accepted as an official member of the European Heat Pump Association's (EHPA) quality control committee, setting up a national quality committee consisting of heat pump manufacturers, the Finnish Innovation Fund Sitra, trade associations including SULPU, and VTT Technical Research Centre of Finland (Talotekniikka, 2010). During 2008–2010, significant lobbying by EHPA (and SULPU) to get heat pumps recognized as a renewable resource under the European Commission Renewable Energy Directive (RES, 2009/28/EC) (European Commission, 2019b) was successful, and led to also EHPA coordinating training programs for the sector (Majuri, 2016). EU level development also meant that heat pumps were included in the national energy aid in Finland in 2011–2012, which is when diffusion greatly accelerated. As part of that policy, which provided grants for building heating system renovations, heat pumps received 20 million Euros, increasing sales by 72% compared to previous year (Virkkunen, 2017). In 2011 for example, 50% of households building their own new homes had chosen ground source heat pumps (Lauttamäki, 2018). The energy grants introduced in 2003 were nevertheless removed for all but low income households in 2013 (Kern et al., 2017).

In 2013, an updated climate and energy strategy concluded that Finland was on track to meet its 2020 renewables aspirations. In the same year, the Finnish renewable energy industry gathered under a joint umbrella organization when the Finnish Clean Energy Association was established, including also SULPU as one of its founding members (Lahienenergia, 2019). Heat pump sales continued throughout the 2010s, and SULPU, which collects sector statistics also used by the Finnish national statistics, has reported year-on-year steady increases in sales. In

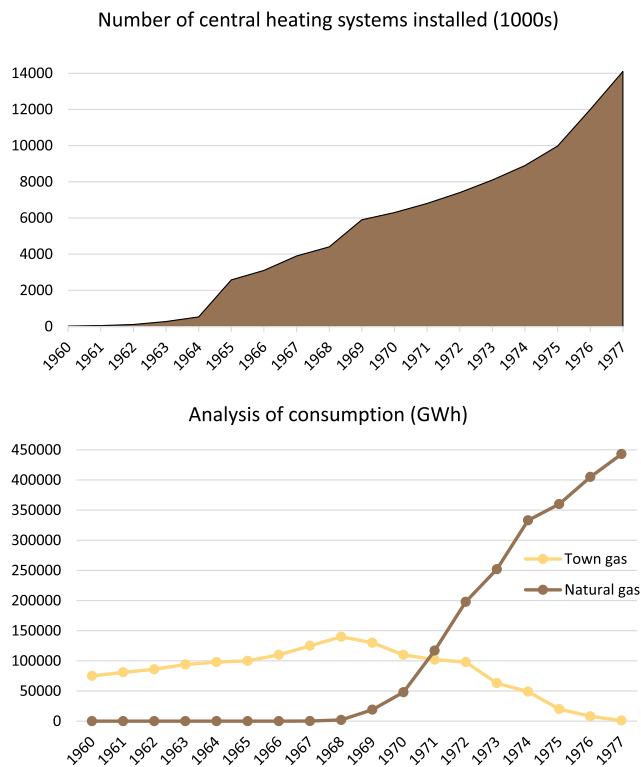


Fig. 4. The rapid transition to gas central heating in the United Kingdom, 1960–1977

Source: Authors, based on data from Arapostathis et al., (2013) and Gross and Hanna (2019).

2017, the national renewable energy target was further increased to 50% of end use by 2030 (TEM, 2017), with heat pumps set at 6 TWh by 2020 and 7 TWh by 2030 (TEM, 2017). Summer 2018 witnessed the high popularity of heat pumps when re-sellers reported empty shelves in their warehouses—heat pumps had sold out during a heat wave as more households have also started to install the technology for cooling.

6. United Kingdom: Gas central Heating (1960–1977)

The United Kingdom is home to our final heating transition, one that occurred in the 1960s and 1970s, and one that involved simultaneous fuel switching as well as the installation of new end-use devices into homes. This transition emerged largely as a way to tap into the newly discovered (and vast) natural gas resources of the North Sea. It saw the creation of household heating dominated by a gas network driven centrally by Gas Boards, with strong state involvement and a vision of seeing the UK become a gas energy economy.

Before the 1960s, most households relied on heat either from woodstoves or via “town gas”, made from the carbonization of coal (Arapostathis et al., 2013). The discovery of natural gas in the North Sea provoked a national program to better transform the country’s energy mix, with a state-managed and centralized program requiring modifications to household appliances (especially burners) as well as the creation of an integrated gas network. In 1966, a single transition was approved to a unified gas infrastructure that required the replacement of 40 million household devices among 14 million homes. By 1977, this network was largely created and 46% of homes had gas central heating (Gross and Hanna, 2019). As Fig. 4 indicates, the United Kingdom thus transitioned from 20,000 gas central heating systems in 1960 to 14 million in less than two decades, or from 0.001% of homes to almost half (46%) of homes in 1977. Corresponding fuel consumption went from

almost entirely town gas in 1966, to almost entirely natural gas by 1977. To illustrate the magnitude of the conversion process, consider that one appliance manufacturer, the Radiation Group of companies, provided conversion sets for over three million cookers, two million water heaters, 1.7 million fires and 52,000 central heating units (Hanmer and Abram, 2017). Some Gas Boards, such as Mercer of South Eastern Board, stated that they had to visit each of the 1.6 million domestic customers in their region *at least five times* (Hanmer and Abram, 2017).

Although the transition to gas central heating only truly begins in the 1960s, after both the discovery of North Sea gas and a national program to convert households in 1966, the seeds for its genesis occur much earlier. After the end of World War II, the Gas Act of 1948 moved towards the nationalization and centralization of previously hundreds of separate gas companies, creating instead a federal governance system with the Gas Council and 12 Area Boards (Arapostathis et al. 2013, 2014). These Area Boards were responsible for the gas industry within their jurisdictions; for planning of demand; for management of the gas network; for maintenance and repair; and for domestic and industrial end uses. A few years later, in the 1950s, the British Coal Utilization Research Association innovated and developed a hot-water central heating system described as “small bore” as it could be installed more easily and cheaply than larger bore systems, creating new opportunities for gas central heating in homes (Gross and Hanna, 2019). The 1956 Clean Air Act further set restrictions on the burning of coal and coke, which also encouraged consumers to adopt central heating systems that could better guarantee minimum temperatures for space heating. By 1960, an estimated 20,000 homes had shifted to gas central heating.

It was also during this time, in the late 1950 and early 1960s, that demand for heating services in the household began to change as new cultural norms and aspirations emerged. Before 1960, most homes were simply heated by open coal fires, and very few households had any heating in bedrooms. However, from 1957 to 1962 households began to debate the merits of a range of different options, including room heaters and central heating, warm air systems and hot water radiators, as well as the pros and cons of coal, oil, electricity, and gas as fuels (Hanmer and Abram, 2017). Strategically tailored advertising campaigns however strongly suggested the need for whole-house heating and the labor saving and convenience attributes of automated boilers. The Gas Council managed an advertising campaign in the 1960s that marketed the value of “high speed gas” and the efficiency and speed by which gas appliances could cook and heat faster, attributes marketed towards women (Arapostathis et al., 2013). Gas Councils and suppliers also ran a “Guaranteed Warmth” marketing campaign in 1969 to offer a fixed price bundled package of boilers, radiators, and installation with guarantees for workmanship as well as achieved temperatures in the home (Hanmer and Abram, 2017). Shell ran a “Mrs. 1970” campaign to raise expectations of thermal comfort and increase familiarity with boilers (Gross and Hanna, 2019). This created a social legitimization of central heating and also changed perceptions of appropriate levels of thermal comfort (Arapostathis et al., 2013).

These technical, marketing, and demographic trends culminated in a national plan to convert households from town gas to natural gas in 1966, including the need to change non-aerated gas burners to specially designed premixed aerated burners and appliances in millions of homes (Arapostathis et al., 2013). This was done in tandem with efforts to further develop infrastructure to tap into North Sea gas reserves, which the Gas Council and British Gas Corporation had secured exclusive monopoly rights to the sale of gas with the 1965 Gas Act (Arapostathis et al., 2014). This meant the Gas Council and the Area Boards exercised extensive power and rights in the management of the flows, distribution and sale of natural gas. With an abundant and adequate supply of fuel guaranteed, whole house heating (fueled mostly by natural gas) grew from less than one million homes in 1960 to more than 2.5 million homes by the end of 1965 (Hanmer and Abram, 2017).

The conversion of Buckingham Palace, Parliament, the Bank of England and Westminster Abbey were also highly visible publicly and

Table 2

The polycentric governance dynamics of rapid household heating transitions.

Category	Dimension	China	Denmark	Finland	United Kingdom
<i>Equity and co-benefits</i>	(1) Use of public funds, loans, subsidies, and taxes	+	+	+	+
	(2) Cost-sharing	+	+	+	
	(3) National policy targets	+	+	+	+
	(4) Co-benefits and positive externalities	+	+	+	
<i>Inclusivity and local involvement</i>	(5) Emphasis on domestic use	+	+	+	+
	(6) Prioritization of rural areas	+	+	+	+
	(7) Involvement of users			+	
	(8) Incentives for local private firms and enterprises	+	+		+
<i>Information, demonstration and innovation</i>	(9) Dissemination of data, information, and knowledge	+	+	+	+
	(10) Active marketing or demonstration programs	+		+	+
	(11) Technological learning	+	+	+	+
	(12) Innovations in technical performance	+	+	+	+
<i>Ownership and accountability</i>	(13) Household or community ownership	+	+	+	+
	(14) Improvement of standards	+		+	+
	(15) Compulsory use requirements and/or penalties for non-compliance	+	+		+
	(16) Scaling back of subsidies	+	+	+	+
<i>Organizational multiplicity</i>	(17) Various government actors (local, municipal, provincial, national)	+	+	+	+
	(18) Industry and industrial organizations	+	+	+	+
	(19) Civil society groups and research institutes		+	+	+
	(20) Transnational actors	+		+	+
<i>Experimentation and flexibility</i>	(21) Experimentation in technical design	+	+	+	+
	(22) Multiple uses, applications or configurations	+	+	+	+
	(23) Progression of scalable targets	+		+	+
	(24) Adaptability in transition management	+		+	+

Source: Authors

further enhanced confidence in gas as a fuel (Arapostathis et al., 2013).

In the 1970s, the Gas Act of 1972 further consolidated and centralized the control over gas, and the Gas Council was renamed the British Gas Association (Arapostathis et al., 2014). By 1972, 6 million consumer appliances had been converted and by 1977 the whole program was completed, reaching 40 million appliances and 14 million users (Arapostathis et al., 2013). At this time, 92% of the population in the United Kingdom also had a gas grid connection (Hanmer and Abram, 2017). The gas central heating transition in the UK thus demonstrates how a consortium of government planners, gas area boards, gas companies and marketers managed a major household transition that altered fuel supply chains and infrastructures, household appliances, and user perceptions of heat and comfort (Foxon et al., 2013). It also underscores a degree of lock-in, with the gas network still the prevailing form of heat supply in the United Kingdom today, clearly showing how decisions made in the 1960s have locked the country into gas-based heat (Gross and Hanna, 2019).

7. Discussion: The polycentric governance of the four heating transitions

As the governance literature predicted, a set of qualitative variables does seem predisposed towards more effective climate and energy governance (Ostrom 2009a, 2009b). These include *equity and co-benefits*, or proportional equivalence of costs and benefits that avoid having some users get all of the benefits at little cost. In the heating transitions, this occurs via the use of public subsidies, cost sharing, targets, and the broad dissemination of co-benefits. *Inclusivity and local involvement*, or the active involvement of a diverse number of stakeholders, was usually brought about by participatory incorporation of local actors in the planning process. In the heating transitions, this includes households and users, rural areas, and the private sector. *Information, demonstration and innovation* includes the distribution of data about costs and benefits. In the heating transitions, this encompasses active marketing programs, technological learning and feedback, and improvements in technical performance. *Ownership and accountability* mean the users bear some of the costs of governance themselves and are accountable for their actions. In the heating transitions, this was achieved through strong standards, graduated sanctions to enforce rules and penalize noncompliance, and that subsidies are eventually scaled back. *Organizational multiplicity*

means that multiple actors were involved to deepen coverage and offer parallel systems of governance. In the heating transitions, this included various government actors (at all scales), industry, civil society, and transnational actors. *Experimentation and flexibility* mean that mechanisms are in place to handle unforeseen events and take an open approach to management. In the heating transitions, this is reflected by experimentation in design, multiple potential uses and configurations, scalable targets, and adaptability in transition management. Table 2 matches these six variables with 24 district dimensions or manifestations.

This section elaborates on the presence of these variables and dimensions for each of the case studies.

7.1. Equity and co-benefits

Equity, or the equal distribution of benefits and/or sharing of costs, seems to play an elemental role in effective heating governance. This plays out through the use of public funds or taxes, cost-sharing, national policy targets, and/or the achievement of positive externalities or co-benefits.

The Chinese solar thermal transition, for example, utilized an abundant portfolio of public resources. This included binding national targets across multiple Five Year Plans (Huang et al., 2012). It also involved the generous use of public funds to promote household systems, including low-cost loans, tax rebates, research grants, and even reduced land provided by municipal governments (Urban et al., 2016), although households still had to commit their own resources to purchase systems. Solar also gained added legitimacy and acceptance due to its large manufacturing base, which resulted in employment in many regions of China and a growing export market. Li et al. (2011) for instance note that three out of every ten jobs in Dezhou are solar-related, thus involvement as workers also encourages local consumers to support the local economy. Solar became such a success that local bureaucrats who managed to attract firms to their province or municipality were often given promotions, based on the knowledge that such firms brought employment, tax revenues, growth, and competitiveness (Urban et al., 2016). Another co-benefit was mitigation of climate change. Urban et al. (2016) estimate that in 2015 solar thermal heating incapacity saved 75.7 million tons of annual carbon dioxide emissions.

Denmark funded their research on CHP through taxes so that its costs

were spread among all electricity customers. Such taxes were equitable because they were based on the amount of energy consumed and funded just by ratepayers instead of all taxpayers (or externalized to society). Denmark also attempted to partially account for the “external” costs of climate change by inducing a carbon tax. Their carbon tax ensured that some of the costs related to carbon dioxide emissions were borne by those responsible instead of shifted to Danish society at large or other countries. Such taxes made oil-based heating expressly less competitive (Roberts and Geels, 2019). Consequently, CHP was able to achieve substantial environmental co-benefits. Mortensen and Overgaard (1992) credit CHP with being instrumental in Danish reductions of carbon dioxide of 20% below 1990s levels by 2005, also as well as a reduction in sulfur dioxide by 60% and nitrogen oxides by 50%.

Heat pumps were and are promoted in Finland as a way to capture externalities such as the decarbonisation of the household heating sector, displacement of fossil fuels, increasing self-sufficiency, and meeting European targets for renewable energy and energy efficiency simultaneously (SULPU, 2018b; Hyysalo et al., 2018; TEM, 2008). Public subsidies for heating system renovations were available for all households during the 2000s, while taxes for fossil fuels continued to rise. These encouraged energy efficiency improvements and a move away particularly from oil-based heating systems, enabling the provision of cleaner heating options such as heat pumps. In addition, the heat pump transition has created jobs in manufacturing, installation and maintenance, with SULPU estimating that in 2017 the sector employed 3000 people in Finland (SULPU, 2019b).

The United Kingdom heating transition was equitable in the sense that it set a mandatory program of appliance replacement and also a mandatory (nationalized) system of gas supply via a gas grid connected to the North Sea. The program operated with distinct targets and it also relied on a mix of funding from the government but also households, who had to purchase their own central heating systems. The United Kingdom program also created an improvement in air quality, as transition from coal to gas reduced emissions not only nationwide but especially in large cities such as London.

7.2. Inclusivity and local involvement

Inclusion, especially the inclusion of rural actors, homeowners, and stakeholders (instead of just urban actors, commercial firms, and select groups) can enhance the effectiveness of climate and energy governance. Inclusivity can be encouraged by incentives for local firms and enterprises as well.

As an example, China heavily promoted the domestic use of solar thermal (rather than intending it for only export markets) and also erected a substantial domestic industrial manufacturing base and a network of dealers. It also strongly pushed solar thermal devices in rural areas (Wang et al., 2017). Urban et al. (2016: 539) even write that due to this intentional focus, solar thermal has become “abundantly available everywhere in China and it has become the ‘standard’ way of heating water in rural areas.”

In Denmark, guaranteed access to the district heating grid minimized barriers to market entry and also established an extensive network of heat pipes, some of them across multiple municipalities. District heating systems in urban areas were owned by municipalities and in rural communities owned by smaller cooperatives (Roberts and Geels, 2019). A coexistence between more urban and centralized district heating systems, and more rural and distributed district systems, thus emerged (van der Vleuten and Raven, 2006). Smaller urban municipalities and rural cooperatives became system owners alongside the more conventional big utilities.

In the Finnish case, households have been actively involved in innovating in heat pump deployment, with users providing peer-to-peer support in “scaling, choosing, comparing, maintaining and modifying” new technologies (Hyysalo et al., 2017: 71). Hyysalo et al. (2013b: 492–493) found that users were modifying heat pumps so that they

would be better suited to the Finnish cold climate. Peer-to-peer support has also taken place especially through Internet discussion forums, which have become integral in sharing information not only about the technology but also about user inventions and innovations that were developed in the early phase of the heat pump sector (Hyysalo et al., 2013a). Moreover, various energy grants were available from the government between 2003 and 2013 to make heat pumps more affordable and inclusive to all, including both urban and rural areas. These were administered by governmental agency The Housing Finance and Development Centre of Finland (ARA) and supported energy renovations, though often with limited resources and timelines, and in 2013 the energy grants were removed for all but low-income households (Lauttamäki, 2018).

In the United Kingdom, the entire heating transition prioritized domestic energy resource use, rather than foreign or export markets, and it focused equally on urban and rural areas. It lastly involved local gas boards and suppliers as well as marketing firms and retail franchises. The British program demonstrates that concerted action across gas boards and area boards could quickly add up and accumulate over time.

7.3. Information, demonstration and innovation

Monitoring, information, and feedback also appear to play instrumental roles, at least in terms of having demonstration programs, and facilitating technological learning and innovations in technical performance.

In China, firms such as Himin undertook extensive marketing and demonstration activities to educate communities, households, and even policymakers about solar thermal applications, in some cases even relying on entertainment and shows (Huang et al., 2017). Technological learning and innovation occurred as well, with solar thermal companies such as Himin, Sang Le, and Linuo executing joint ventures and research projects with Tsinghua University in Beijing or Jiaotong University in Shanghai (Goess et al., 2015). Consequently, the thermal efficiency of solar thermal units improved over time, as did performance, lifetimes, and costs (Huang et al., 2019; Hu et al., 2012). Even more strikingly, Chinese firms are estimated to hold about 95% of the patents for core technologies of solar thermal technology worldwide (Goess et al., 2015).

In Denmark, municipalities and cooperatives did showcase various district heating demonstration projects (Sperling et al. 2011). The Danish Energy Agency also served as a focal point for sharing data and knowledge about pilots and other implementation experiences (Roberts and Geels, 2019), which it then disseminated to community and private sector stakeholders.

In Finland, information and demonstrations were a critical part of the heat pump transition. SULPU in particular developed tools to track and compile statistics on the sector’s development and growth, and they have provided these since 1996 (see SULPU 2018c)—these statistics are subsequently used by the Finnish National Statistics as well as government regulators. SULPU’s strategy was to “influence heat pump sector development in national and international networks” and “support the growth of the sector, provide training and improve quality together with legislators and authorities.” (SULPU, 2018b, translated from Finnish, p. n/a). This included more targeted activities such as aiming to influence policymakers and other key stakeholders especially when new regulation or decrees were planned or prepared. Motiva, meanwhile, run several energy awareness raising activities across a range of stakeholders from school children to industry (Kivimaa, 2014), as well as heat pumps demonstration programs. Finally, user-led online forums have been shown to act as important peer-to-peer sharing platforms in terms of scrutinizing market actors, as well as previously mentioned technical tests on heat pumps (Hyysalo et al., 2018).

In the United Kingdom, technical innovations occurred hand-in-hand with a focus on shaping user preferences and demand for heating. The Gas Council and others such as Shell had campaigns such as “Mrs. 1970,” “High Speed Gas” and “Guaranteed Warmth” (Pearson and Arapostathis,

2019). The Gas Council and Area Boards piloted training and innovation programs with technicians, called “converters,” and also had “crash programs” where they worked on acclimatizing institutions and the public to be confident in the new fuel (Arapostathis et al., 2013). The Gas Council and Area Boards were even self-described as an “experiment in cooperation by consent” (Foxon et al., 2013), as they were able to coordinate and develop research activities on gas technologies as well as delivery systems. The British Coal Utilization Research Association also popularized central heating and the idea of household heating controls (Hanmer and Abram, 2017).

7.4. Ownership and accountability

Each of the four case studies created conditions that enhanced ownership and the accountability of producers and users. In some situations this occurred through the enactment of standards, in others compulsory requirements (mandates) for use. Many programs however lastly scaled back subsidies or support when it became apparent the transition no longer needed heavily steered.

China directly incentivized the direct ownership of solar thermal systems with rebates and other financial incentives. It also established a strong regime for testing, standards, and certification. The government partnered with the United Nations Development Program to create a testing and certification system for solar water heating systems, with facilities for testing in Beijing, Kunming, and Wuhan (Tao, 2010). This was followed by three separate private certification schemes, including Golden Sun for general verification, Ten Ring for environmental certification, and China Academy of Building Research for building certification (Tao, 2010). This created a quality guarantee system that ultimately incorporated 20 separate testing regimes and standards (Hu et al., 2012). China supplemented these efforts with compulsory use in many areas, with numerous cities and municipalities mandating that new buildings use solar thermal systems for hot water or heating. China lastly calibrated and scaled back subsidies for solar thermal, with Urban et al. (2016) writing that by 2015, “Today there are only few formal subsidies at the national level and there is a limited amount of industrial policy that supports the growth of the solar water heater industry.”

Denmark also ensured heat services were not given away for free and instead commercially viable. Mortensen and Overgaard (1992) write about how the business model for Danish CHP revolved around the idea that heat is sold as a service that consumers pay for. Heat providers and companies were given low-interest loans with typical planning periods of 15–20 years, with an understanding that revenue yields would be slow but steady, and that some systems may last longer than 50 years to justify the investment. Moreover, CHP units were required to replace district heating units, and their previous use of oil, diesel, and coal was prohibited and replaced by natural gas (Hendriks and Blok, 1996). If the local market was not large enough to cater to cogeneration, the district heating plants were required to utilize biomass. Concomitantly, all large utilities in the major cities were ordered to use biomass (especially straw), and required to obey mandatory energy efficiency regulations (van der Vleuten and Raven, 2006).

In the Finnish heat pump case, industry developed standards early on, increasing the reputation of a previously tarnished market, while connecting together with a governmental agency Motiva gave the heat pump association SULPU better credibility (Majuri, 2016; Virkkunen, 2017). Finland’s membership of EHPA also gave access to EHPA-coordinated training and certification scheme EUCert, which was developed in accordance with the European RES Directive (European Commission, 2019b; Majuri, 2016). Furthermore, Finnish legislation on the requirements of training providers offering heat pump certification courses was developed in 2015 following European directives (Finlex, 2019; European Commission, 2019b). Motiva, meanwhile, holds a database of certified installers. Online user forums too were sharing their experience of market players, acting as unofficial product, manufacturer and installer testers (Hyysalo et al., 2018).

In the United Kingdom, all four elements were present. Households were not given free central heating systems, they instead had to purchase packages, although appliance conversion was sponsored by the government. Rigorous standards were in place to ensure both the calorific quality of natural gas and the efficiency and performance of the new aerated burners. Multiple compulsory regulations pushed the transition, including the 1956 Clean Air Act (which made a focus on smokeless fuels and areas, and thus the conversion of boilers to gas or electric heat). The later nationalization and centralization of gas put the Gas Council in a privileged position to coordinate action and prioritize public investments in new infrastructure (Pearson and Arapostathis, 2019). However when the program ended in 1977 all subsidies were withdrawn, even though gas central heating went on to reach 92% of houses in 2014 (Gross and Hanna, 2019).

7.5. Organizational multiplicity

Each case demonstrates some of the benefits of organizational multiplicity, or having multiple stakeholders with overlapping spheres of responsibility across many scales (local, state, national) and sectors (government, industry, civil society), some even transnational actors.

China saw a complex array of multiple types of institutions support solar thermal adoption, from the central government to provincial governments and even dozens of cities with their own strong policy regimes (Huang et al., 2018). Goess et al. (2015) write about how six distinct stakeholders influenced the success of solar thermal diffusion, including industrial firms, city and national planners, real estate businesses, social energy associations, universities, and political parties. Li et al. (2011) similarly point out the importance of central government, municipal government, the solar industry, solar dealers, and households acting together. As previously mentioned, transnational actors played a role as well, most notably Canadian firms partnering with Chinese institutes in the 1970s and 1980s to perfect evacuated tube technology and the UNDP assisting with standards and certification.

Danish heating policy worked with *kommunes* (municipalities), urban utilities, and rural cooperatives when setting guidelines for CHP plants. National planners also provided appropriate tariffs and clear guidelines about minimizing the use of oil and coal while local planners carried out heat plans and accelerated the connection of buildings to district heating. Roberts and Geels (2019) affirm that the Danish heat transition to CHP benefitted greatly from the coordination between governmental entities, non-profit cooperatives, financiers and banks, and those designing heat systems.

The establishment of SULPU has been credited as an important step for the Finnish heat pump sector as it brought together both GSHP and ASHP players (Lauttamäki, 2018). Furthermore, the association created an important industry-research-government link early on in market formation. The Finnish heat pump sector has had transnational involvement from firms in the Swedish heat pump market, EHPA as well as the International Energy Agency. Furthermore, there were links nationally between SULPU, research organizations (e.g. through the Finnish Innovation Fund, VTT Technical Research Centre of Finland), and other trade associations (Finnish Refrigeration Enterprises Association, Finnish HVAC Association SuLVI (Talotekniikka, 2010). Also, larger industrial players in the energy and non-energy sectors, such as the metal-based component industry, have been involved, especially in the GSHP sector since 2000s (Lauttamäki, 2018).

The United Kingdom involved nationalized and state affiliated entities such as the Gas Council and Area Boards but also appliance manufacturers and fuel suppliers (e.g. Shell). These worked with local municipalities and also civil society or industry groups such as the Society of British Gas Industries and the British Coal Utilization Research Association, plus universities. It was thus a highly coordinated and complex institutional arrangement.

7.6. Experimentation and flexibility

Each case study has elements of experimentation and flexibility in programmatic design, or in technological configuration, or a progression of targets (scaling up) and adaptable management.

China did not set rigorous restrictions on the type or size of solar thermal systems, with flat plate collectors eventually coming to make inroads into the market alongside evacuated tube systems. Li et al. (2011) note a diversity of other applications and products as well, including centralized solar bath houses built by local governments. Other innovators sought to scale up household designs to solar industrial applications such as paper, machine manufacturing, and textiles (Huang and Liu, 2017; Huang et al., 2019). Other dealers and installers experimented with integrating residential solar thermal systems better into buildings, including balconies; more specialized devices for low temperature or high temperature settings; and trials with solar cooling and air conditioning (Goess et al., 2015). Some municipal planners sought to be flexible as well by relaxing building codes standards so that homes could set up solar water heaters on roofs without planning permission or other tedious rules (Urban et al., 2016). When the national government began to scale back some of its incentives, municipal and provincial planners responded by raising theirs.

Denmark took an open and flexible approach to heat, initially pursuing a mission driven strategy (reduce dependence on oil and energy imports) rather than expressly mandating a particular technology (Mortensen and Overgaard, 1992). Indeed, heat pumps were debated as a solution in the 1970s and national planners even considered a nuclear-electric heating system before they decided on CHP (Roberts and Geels, 2019). More recently, Danish CHP planners have embraced a diversity of novel options for making heat, including waste incineration (Werner, 2017) as well as solar district heating applications (Tian et al., 2019) alongside biomass and gas.

In Finland, government's decarbonisation policies have included a mix of technologies, with heat pumps included as one part of a renewable energy mix. While in the 1970s many deployed heat pumps were largely ground source heat pumps, and the government supported heat pump manufacturers, both ground source and air source heat pumps have diffused in Finland during 2010–2018. Despite the Finnish bedrock being well-suited for borehole technology (Lauttamäki, 2018), technological developments, and cost reductions, in air source heat pumps have made them better suited in some housing types such as those houses which have limited land opportunities for GSHP borehole drilling. Different types of heat pumps have thus seemed to have complimented each other during the transition. User-innovation, meanwhile, led in some circumstances to the development of new heat pump products, enabling also experimentation beyond incumbent heat pump manufacturers (Hyysalo et al., 2013b).

The United Kingdom was similarly flexible. On the supply side, planners initially considered, and experimented, with many different processes and feedstocks related to gas, including developing North Sea production, oil gasification, imports of liquefied natural gas and pipelines, and deciding to abandon other efforts such as the Lurgi process of coal gasification (Pearson and Arapostathis, 2019). On the demand or end-use side, innovations in aerated burners, boilers, and natural gas ready appliances were also designed, most prominently the “small bore” hot water pipework systems developed by the British Coal Utilization Research Association (Hanmer and Abram, 2017). The program also had explicitly scaled targets that saw a steady progression of diffusion between 1966 and 1977.

8. Conclusions and policy implications

The four national case studies of rapid heat transitions across households in China, Denmark, Finland and the United Kingdom bring to light four salient conclusions. First, they reveal that *deep* or wide-reaching, transformative transitions in heat are indeed possible, with

our four cases collectively changing how more than 100 million households and approximately 310 million people received their heat and hot water. These transitions also affected a wide percentage of their respective populations—with 19.2% of the entire population reached in China, 28.9% in Denmark, 33.9% in Finland and 77.2% in the United Kingdom. That two of these countries—China and the United Kingdom—have comparatively large populations and economies makes the effect of the transition even more striking.

Nonetheless, and second, our cases do suggest we reinterpret what we may mean by the term *rapid* when we consider the “temporality” or “speed” of energy transitions (Sovacool, 2016). The bulk of diffusion in all four of our transitions took 18–35 years to occur. Historically, this is far more rapid than previous European transitions (which took half-centuries to centuries), but far short of recent calls to shift global or national energy systems in five to ten years. Efforts to promote “deep decarbonisation” (Rockström et al. 2017; Geels et al. 2017) or respond to climate “urgency” (Partridge et al., 2018) and climate “emergency” (Markusson et al., 2014; Bromley, 2016) may take more time than we realize. Our cases, at least in the domain of heat, indicate that such rapid transitions are not supported by the historical record. Indeed, this finding that “rapid” transitions can still take more than a decade is implicitly acknowledged in energy and climate planning. For example, the United Kingdom's policy to bring all greenhouse gas emissions to “net zero” stipulates 2050 as the end date, more than 30 years from now. Moreover, Denmark's most recent climate law (passed in 2019) seeks to reduce emissions by 70%, but by 2030–11 years from now, while Finland pledged in June 2019 to become carbon neutral by 2035. In this context, rapid can still mean somewhat sluggish.

Third, our cases implicitly recognize the utility, or even the necessity, of spatial and technological *variation* in transitions. Three of our rapid and deep cases did occur in Europe, but even then they accelerated across a range of timeframes (Britain's in the 1960s, Denmark's in the 1970s, Finland's in the 2000s) and types of energy markets (state-controlled versus more open and competitive). The Chinese case is striking because it occurred in a non-Western market with significant guidance from state planners. Our transitions were not limited to low-carbon technologies, either—while we see the rapid and deep diffusion of solar thermal heating and hot water in China, and heat pumps in Finland, the district heating transition in Denmark utilized a hybrid of fossil fuels (e.g., gas instead of coal) and renewables (e.g., biomass and straw) and the United Kingdom central heating transition was entirely fossil fueled. The implication here is that energy transitions scholars can learn perhaps just as much from fossil fuel transformations as they can from low-carbon or renewable ones—even if their aim is to distill and apply such insights to the current goals of global decarbonisation.

Fourth and finally, our cases remind us that how programs are governed can be as equally important as the specific technologies being utilized or the policy incentives in place. When governed well, poly-centric approaches to heating transitions can offer an equitable, inclusive, informative, accountable, protective, and adaptable framework for promoting new heating systems or practices. China stimulated industrial research with strong municipal and national targets and policies to the point where they saw adoption rates for solar thermal systems surpass 95% market penetration in many urban areas. Denmark blended small-scale decentralized community control with national standards and policies to promote district heating so it reached 80% of household needs. Finland harnessed users, peer-to-peer learning, and innovation alongside national and European policies and incentives so that heat pumps reached almost a third of all homes. The United Kingdom coordinated a nationalized Gas Council and Area Boards with industry groups, appliance manufacturers, installers and marketing campaigns so that gas central heating reached almost half of all homes.

A key element in all of these cases was a central state willing to coordinate and steer programs and policies, but also to intervene and invest in purposive action that facilitates the roles of industry groups, civil society actors, and households themselves. As Fig. 5 summarizes,

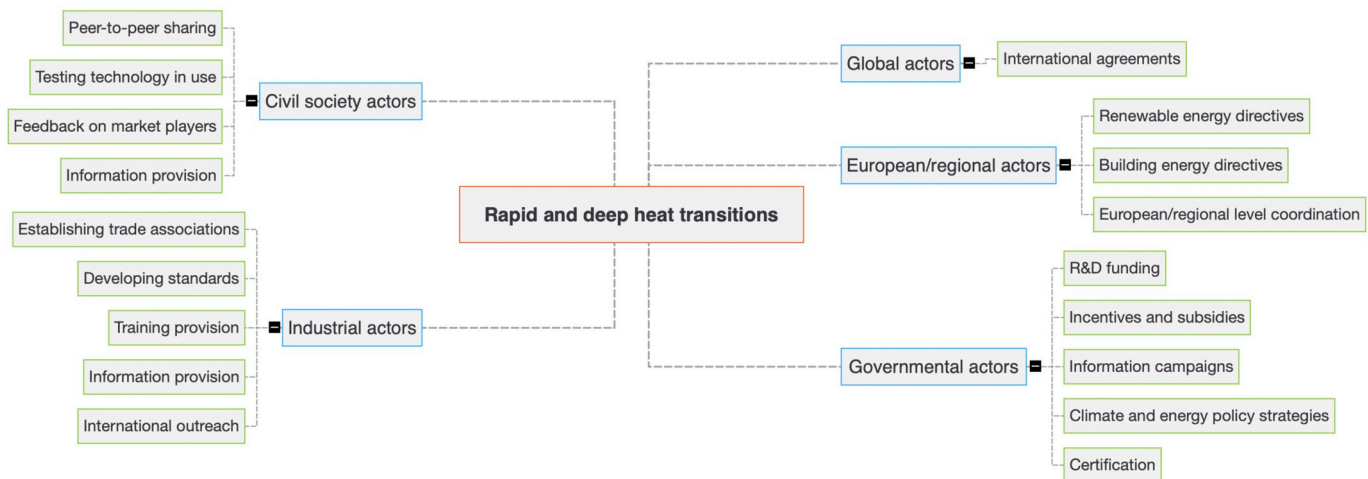


Fig. 5. Polycentric governance dynamics of four rapid and deep heat transitions
Source: Authors.

such a polycentric design ensures the beneficial involvement of multiple actors that can facilitate feedback, develop standards, promote agreements, align incentives, and otherwise shape each heating transition in a multitude of positive dimensions.

The success of these four polycentric heating transitions reminds us that when multiple actors at a variety of scales must perform in overlapping areas, they can often promote innovation as well as cooperation and citizen involvement. It also suggests that if one is going to design future heating transitions, they ought to seriously consider a polycentric lens, given that polycentrism is confirmed in our cases to promote dialogue, provide a regulatory safety net, enhance accountability, and maintain economies of scale in the context of energy security and climate change mitigation. Planners and especially engineers often focus on responding to the need to decarbonize heat by perfecting a particular technology, such as a hydrogen fuel cell or a hyper-efficient boiler. However, this study affirms that designing the right sort of political and governance architecture can be just as salient. National policy can perhaps engender a *rapid* transition—with China's National Building Energy Efficiency and Green Building Development and National Solar Energy Development programs, Denmark's Energy Policy of 1976, Finland's 2001 National Climate Strategy, and the United Kingdom's Gas Act of 1948 all coming to mind as significant policy drivers. But it is polycentric governance that potentially ensures it can be *deep* and transformative.

Declaration of competing interest

None.

CRedit authorship contribution statement

Benjamin K. Sovacool: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Mari Martiskainen:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing.

Acknowledgments:

The authors gratefully acknowledge support from UK Research and Innovation through the Centre for Research into Energy Demand

Solutions (CREDS), grant reference number EP/R035288/1. This paper has also received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 764025. The content of this deliverable does not reflect the official opinion of the European Union. Responsibility for the information and views expressed herein lies entirely with the author(s).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enpol.2020.111330>.

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